

Evolution of solar magnetic tubes and its manifestation in Stokes parameters

V.A. Sheminova and A.S. Gadun

Main Astronomical Observatory, National Academy of Sciences of Ukraine
Zabolotnoho 27, 03689 Kyiv, Ukraine
E-mail: shem@mao.kiev.ua

Abstract

Basic scenarios and mechanisms for the formation and decay of small-scale magnetic elements and their manifestation in synthesized Stokes profiles of the Fe I 15648.5 Å infrared line are considered in the context of two-dimensional modeling of nonstationary magnetogranulation on the Sun. The stage of convective collapse is characterized by large redshifts in the V profiles accompanied by complete Zeeman splitting of the I profiles. This is due to intense downward flows of material, which facilitates the concentration of longitudinal field with an amplitude of about several kG in the tube. The dissipation of strong magnetic structures is characterized by blueshifts in the Stokes profiles, which result from upward fluxes that decrease the magnetic field in the tube. Typical signatures during key stages in the evolution of compact magnetic elements should be detectable via observations with sufficiently high spatial and temporal resolution.

1 Introduction

Studies of the interaction of thermal convection with magnetic fields via numerical modeling of magneto-convection [1, 2, 4, 7, 9, 10, 11] are of considerable interest for our understanding of the structure and dynamics of small-scale magnetic fields, which carry most of the magnetic flux going from the solar photosphere, outside of pores and sunspots. Current time-dependent magnetohydro-dynamic (MHD) models can successfully describe the observed concentration of magnetic flux in intergranular regions and explain variations in convection under the influence of magnetic fields. They also enable detailed study of mechanisms for the formation of compact magnetic elements and their evolution. Unfortunately, verification of MHD models and direct comparison with observations are not easy for a number of reasons, such as the limited spatial resolution of the observations. One link between observations and MHD models is provided by Stokes diagnostics, which are now well developed. These represent a set of special methods for extracting information about the structure and dynamics of magnetic elements from spectropolarimetric observations. The use of Stokes diagnostics to study the structure of small-scale magnetic elements is necessitated by the fact that these elements are smaller (70–300 km) than the spatial resolution of modern instruments, so that the observed signal carries information not only about the magnetic structures, but also about the nonmagnetic surrounding environment. As a result, correct interpretation of such observations is difficult.

The aim of the present work is to study evolutionary changes in the structure and dynamics of magnetic elements, as well as variations in the parameters of synthesized Stokes profiles, via two-dimensional modeling of nonstationary magnetogranulation. We also wish to identify diagnostic signatures characteristic of magnetic-field intensification and dissipation.

The numerical modeling of nonstationary magneto-convection we consider here was carried out for two hours of real solar time, and describes both the formation and dissipation of small-scale magnetic elements. In particular, precisely such modeling demonstrated for the first time the importance of the surface mechanism (scenario) for the formation of compact magnetic elements, which is realized during the fragmentation of large-scale thermal fluxes. This mechanism is described in detail by Gadun et al. [5], who also present the preliminary results of the modeling. These results are analyzed in more detail in [4], along with investigations of the formation and decay of tubes, tube stability regimes, differences in the brightness characteristics of magnetic and nonmagnetic granulation, and the dependences of magnetic-element parameters on their horizontal scales and the field intensity. Extensive test-diagnostic calculations—in particular, the synthesis of Stokes profiles of several spectral lines and comparison with observations—were conducted for the same models in [14]. These models adequately describe the basic features of spectropolarimetric observations of compact magnetic elements. Another important result of [14] was testing the available Stokes diagnostics methods, which was done by comparing the model parameters with those derived from an analysis of theoretical spectropolarimetric scans.

The present paper represents a continuation of these studies. It describes in more detail several critical stages in the evolution of compact magnetic elements that can be detected via spectropolarimetric methods. As usual, the small-scale magnetic elements in the numerical modeling will be called tubes, although they do not have a tube shape in a two-dimensional planar representation.

2 MHD models and calculation of Stokes profiles

We estimated all the thermodynamic parameters of the atmosphere required to solve the transfer equations for the spectral lines in the presence of a magnetic field via numerical MHD modeling of planar magnetoconvection of the granulation scales. We made the approximation that the medium was compressible and partially ionized, and was stratified by gravity and coupled with the radiation. The complete system of radiative MHD equations and its solution for the particular case at hand are described in [5]. As an initial model for the MHD simulations, we used nonmagnetic, two-dimensional models whose computation was based completely on the approaches presented in [3].

The upper and lower boundary conditions in the MHD simulations were taken to be free; i.e., there was free inflow and outflow of material. The velocity components were determined by the condition $\partial \mathbf{V} / \partial z = 0$, and the average values of the intrinsic energy and density were fixed by the initial uniform model [3, 6]. The profiles of the fluctuations of these quantities at the upper (or lower) boundary coincide with the corresponding variations for the layers located at lower (or greater) heights. In addition, the density at the lower boundary was scaled so that the sum of the gas, radiative, and magnetic pressures was constant at a fixed horizontal level.

The upper and lower boundary conditions for the magnetic field were specified by its global character and took the form $B_x = 0$ and $\partial B_z / \partial z = 0$. The lateral boundary conditions were taken to be periodic. The initial configuration of the magnetic field was

bipolar, with the field intensity decreasing with height. The average value of B over the entire computational region was 54 G. We chose this configuration to help ensure numerical stability of the solution at the initial simulation time, since the velocity field and thermodynamic quantities, on the one hand, and the magnetic-field characteristics, on the other hand, are not self-consistent in the initial model.

The computational region was 3920×1820 km in size, with spatial steps of 35 km. The atmospheric layers covered about 700 km. It is obvious that we cannot study the intrinsic structure of fine magnetic configurations in detail with such a step size, but it is adequate for following trends in the evolution of magnetic configurations, and reduces the computer time required for the calculation.

To study the evolution of magnetic elements, we considered a sequence of MHD models from time 1.5 min at the beginning of the simulation (when the average magnetic field was about 54 G) to time 120 min (when the average magnetic field was = 500 G). This sequence contains 94 two-dimensional models with time intervals of one minute and 52 models with intervals of 0.5 min. The computational region contains 112 vertical columns (rays). We computed four Stokes profiles for each vertical column for a particular model as for a plane-parallel atmosphere, after which we performed a spatial average of the resulting profiles. The equations for the transfer of polarized radiation in a magnetic field (often called the Unno-Rachkovskii equations) form a system of four first-order differential equations. We used a fifth-order Runge-Kutta-Felberg method to numerically solve these transfer equations. The detailed computation algorithm, description of the software, and behavior of the Stokes profiles as functions of the state of the medium and atomic parameters are given in [8, 12, 13]. The only substantial restriction in the computation of the Stokes profiles is the assumption of local thermodynamic equilibrium.

To study temporal variations in the Stokes profiles, we chose the Fe I 15648 Å infrared line, which possesses very promising diagnostic capability [15]. Along with its high magnetic sensitivity, the important advantages of this line are its low temperature sensitivity and the fact that it is formed in very deep layers of the photosphere (below $\log \tau_5 = -1$). As shown in [14], this line is especially suitable for LTE analyses of theoretical MHD models, in which the temperature fluctuations in the upper layers of the photosphere can be artificially overestimated due to the use of a gray approximation for the radiative transfer.

3 General characteristics of nonstationary magnetogranulation

The results of the numerical simulations show that the character of the evolution of thermal fluxes significantly affects the development of magnetic configurations. The dissipation of granules and merging of intergranular gaps result in the disappearance of small-scale magnetic fields or the formation of cluster-like structures, whereas the fragmentation of granules in the presence of horizontal photospheric fields leads to the formation of new compact magnetic configurations.

Figure 1 shows that the entire simulation interval can be subdivided into three stages [4, 5]: an initial period (up to 20 min), which is primarily determined by the initial conditions; a transition period (from 20 to 35 min), when there is a mutual reconstruction of the magnetic field and thermal convection; and a final period of self-consistent evolution of the nonstationary convection and magnetic field. The first clear signatures of the presence of compact magnetic tubes with strong fields (of the order of several kG) appear after approximately 50 min of real solar time. Bright points form in the intergranular

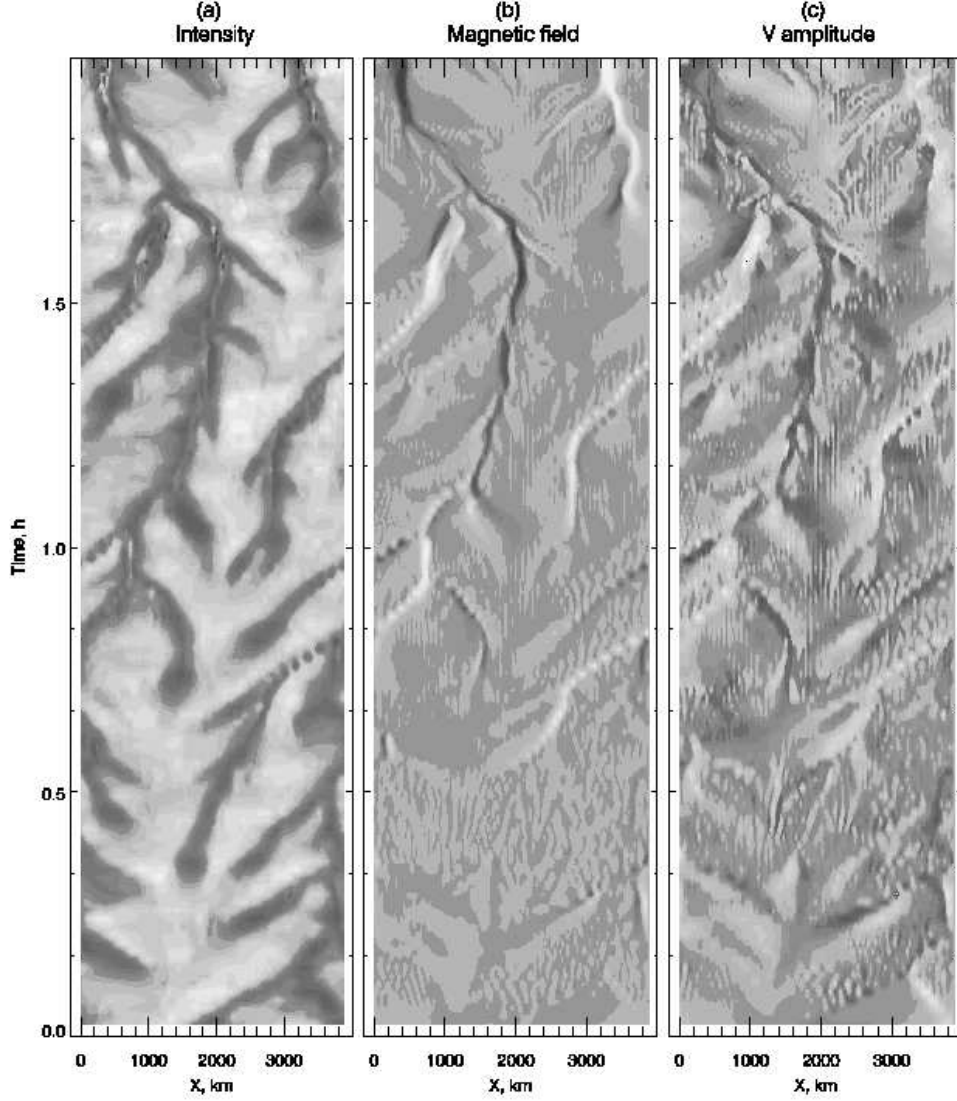


Figure 1: Spatial and temporal evolution of (a) the intensity of monochromatic emission $I_c/\langle I_c \rangle$ at wavelength 500 nm, (b) the magnetic-field intensity B at $\log \tau_R = 0$ level, and (c) the amplitude of blue wing of the Stokes V profile of the Fe I 15648 Å line in the course of two-hour, two-dimensional MHD modeling. The $I_c/\langle I_c \rangle$ variations is 0.017-1.78, and is represented by a linear gradation from dark to light shading. The B variations ranges from -2867 to +2540 G. Negative and positive polarity of magnetic fields are shown by dark and light shading, respectively. The variations in the V profile amplitudes range from -0.14 to 0.16. Negative and positive values are shown by dark and light shading, respectively.

gaps, and the tubes begin to glow. The positions of the bright points (Fig. 1a) correspond to regions of strong magnetic field whose orientation is predominantly vertical or close to vertical (Fig. 1b), and also to regions of increase in temperature, decrease in pressure, and oscillating upward-downward flows in the intergranular gaps.

Due to the effect of the hot walls, the glow of the tubes will begin earlier near the disk edges than at their centers. This suggests the possibility of early observational diagnostics of magnetic elements that have just begun to be formed [2]. Note also that the compact structures with strong magnetic fields that form are often located near regions with relatively weak fields of the opposite direction. The character of the granulation also changes. The magnetic field produces a stabilizing action: there are no strong horizontal shears in the presence of the magnetic field, as distinct from the case of nonmagnetic granulation. The size distribution of the granules in the magnetogranulation also differs from the nonmagnetic case: the granules are smaller, and there are many small-scale bright structures with sizes less than 150–300 km associated with bright points of the magnetic tubes [4].

There are two scenarios for magnetic-tube formation in the numerical simulations under consideration [4]. The first is based on the concentration of a magnetic field between cells and its intensification up to the equipartition level due to a kinematic mechanism; the field can then be further amplified by the development of superconvective instability. The second mechanism is based on the formation of a tube during the decay of thermal convective flux. The magnetic-tube behavior in this case also exhibits two stages. The first takes place when the field intensity has not reached the equipartition level, so that the tube is in a state of convective instability. The subsequent, stronger stage occurs when the upper part of the tube is in radiative equilibrium and experiences an oscillatory instability. The transition from one regime to the other occurs at $B = 1200\text{--}1300$ G [4].

The situation changes abruptly when convective collapse is "turned on." The level of the observable surface of the magnetic tube becomes more strongly dependent on B . The Wilson depression increases. The temperature at the corresponding level also increases, since the observable surface shifts to deeper layers, and the plasma configuration is actively heated by neighboring hotter thermal fluxes. The gas pressure decreases due to the increasing magnetic pressure, and the density also decreases. The tubes begin to glow, and the intensity of their emission is above the average level. The tubes are also surrounded by dark regions, which correspond to channels of intense downward flows of material near the tubes. The brightness peaks of most wide tubes are split due to the effect of the large horizontal scale, which results in less efficient lateral heating. As a result, the total contrast of the tubes increases.

Our simulations revealed three basic mechanisms for the disintegration of the tubes [4]: dissipation of the magnetic field due to reconnection of the field lines, disintegration due to interchange instability, and reversal of the convective collapse. The first case—dissipation of the magnetic field—is the most common scenario. It occurs when the thermal flux separating two tubes with opposite field directions disappears, and the tubes merge. Interchange instability takes place when the orientation of intense magnetic tubes deviates from the vertical. The rising of strong horizontal magnetic field results in the development of flute instability. In the plane case under consideration, this instability can split and dissipate strong compact tubes. Inverse convective collapse [7] is produced by the strong depletion of the upper part of the tube when it is intensified. Such depletion reverses the convective collapse, so that downward flows in the tube are replaced by upward ones, whose velocity can reach supersonic values in the atmosphere [7].

The evolution of magnetoconvection briefly outlined above is analyzed in more detail in [4]. Here, we will compare separate critical stages of tube evolution with Stokes profiles

synthesized for the same simulation times. With this aim in view, we chose the most typical cases for the formation and decay of magnetic tubes from the temporal sequence of MHD models.

4 Examples of evolution of a kilogauss magnetic tube

Figure 1c shows variations in the amplitudes of the blue wings of the synthesized Stokes V profiles over two hours in the simulation region. These changes are very similar to the space-time variations in the magnetic field (Fig. 1b). To illustrate the formation and dissipation of the magnetic tubes, we shall consider in detail only two separate regions of the MHD models, whose evolution is presented in Figs. 2 and 3. The thick curve in the temperature distribution denotes the level $\tau_R = 1$ (where τ_R is the Rosseland opacity), and the dotted curve corresponds to the lowest temperature (4000 K). The vertical dashed line indicates the central axis of the region in which the magnetic tubes are located. Figures 4 and 5 present Stokes profiles of the Fe I 15648 Å spectral line with various spatial resolutions with respect to the central tube axis — 35, 105, 175, and 315 km — synthesized for these regions. Note that a resolution of 35 km corresponds to the horizontal step of the simulation, so that the corresponding profiles were calculated at the tube center without spatial averaging; they are marked by the solid curves in the figures. We determined the parameters commonly used in Stokes diagnostics precisely for these profiles. These parameters are the amplitude of the V profile, $a_V = (a_b + a_r)/2$ (where b and r are the blue and red wings), the magnetic-field intensity (in G) derived from the distance between the maximum peaks of the V profile, $B_{br} = (\lambda_r - \lambda_b)/(2 \cdot 4.67 \cdot 10^{-13} \lambda_0^2 g_{\text{eff}})$ (where λ_0 is the wavelength of the unshifted line center in Å), the shift of the V profile, $V_V = c(\lambda_z - \lambda_0)/\lambda_0 - 2.12 \cdot 10^{-6} c$ (where λ_z is the wavelength of the zero intersection of the profile), and the relative asymmetry of the amplitudes and areas of the V profile, $\delta a = (a_b - a_r)/(a_b + a_r)$ and $\delta A = (A_b - A_r)/(A_b + A_r)$.

4.1 Formation of a magnetic tube

Let us compare the calculated Stokes profiles and their parameters (Fig. 4) with the physical processes of magnetic-tube formation due to the surface mechanism (Fig. 2).

A situation typical for the beginning of fragmentation of a large convective cell with a diameter of about 3000 km occurs in the (3920 × 1820 km) computational region at time 57 min. There is an upward convective flow in its central part ($x = 2100$ km). Two reverse flows, directed from the central regions, can be seen at the periphery. A spot of high-density material appears in the upper layers of the photosphere. The temperature at the $\log \tau_R = 0$ level decreases in regions of weak flow due to radiative cooling. There is a weak horizontal magnetic field with varying direction in the cell. In the predicted region of magnetic-tube birth (whose center is marked by the vertical dashed line in Fig. 2), the calculated Stokes profiles are shifted toward the blue part of the spectrum, $V_V = -0.8$ km/s. The minus sign denotes upward motion. The weak V profile (drawn by the solid curve in Fig. 4) includes two components with opposite polarities (the negative one is quite strong, and the positive one very weak).

The situation at time 59 min is typical for the initial phase of magnetic-tube birth. A downward jet of cold material forms during the fragmentation of the thermal flux (a convective cell). This flow drags the photospheric magnetic field with it, so that the horizontal field is transformed into a longitudinal field. The I, Q, and V Stokes profiles

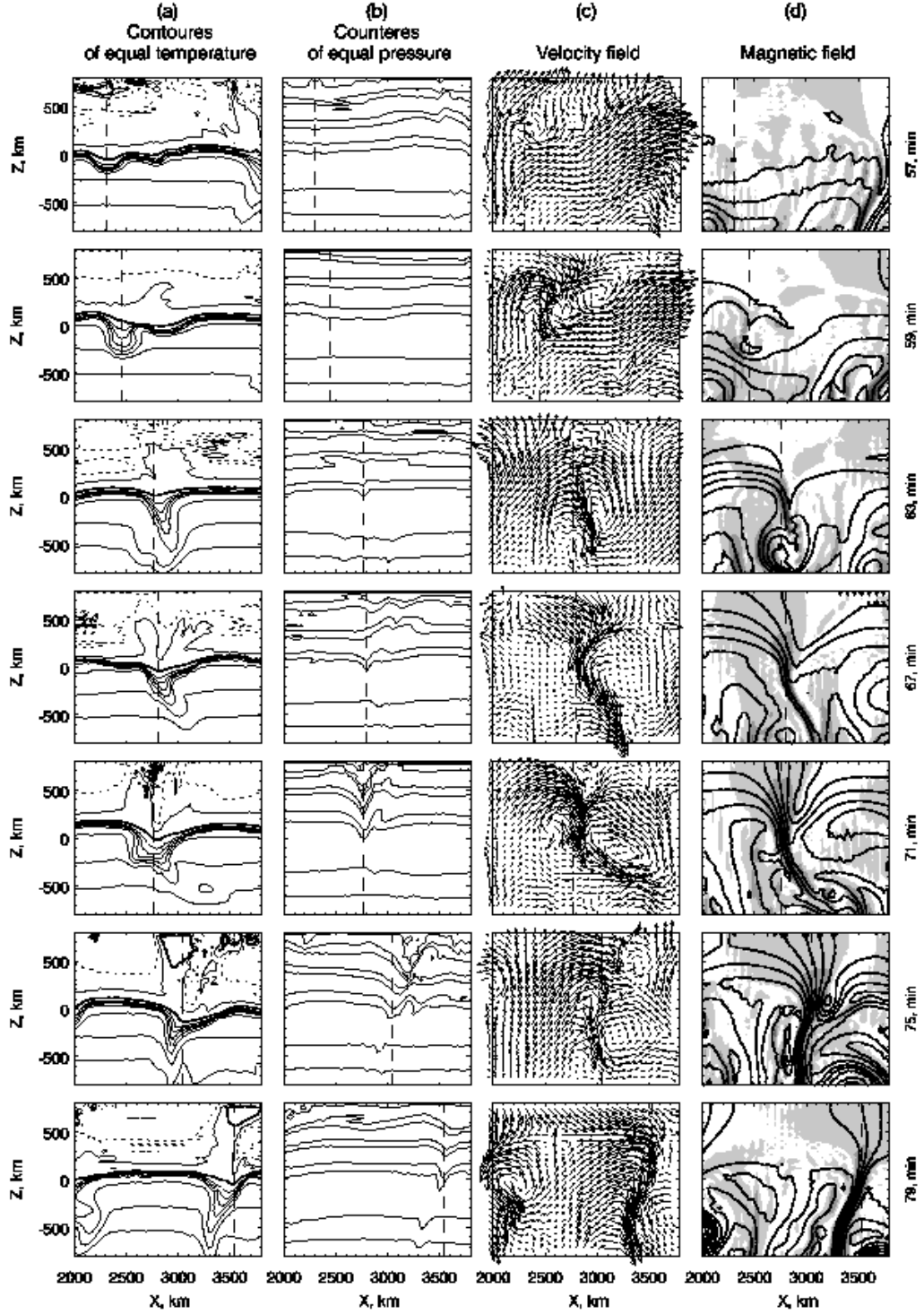


Figure 2: Spatial and temporal evolution of magnetic-tube formation in the simulated region from 2000–3800 km in the time interval 57–79 min: distribution of the (a) temperature T (the dotted curve corresponding to 4000 K and the thick curve to 6000 K show the Fe I 15648 Å line formation region), (b) gas pressure P , (c) velocity field V , and (d) magnetic-field intensity B (the density of the shading is proportional to the values 10, 400, 800, and 1200 G; dark and light regions correspond to positive and negative polarity, respectively). The vertical dashed line denotes the center localization of the tube.

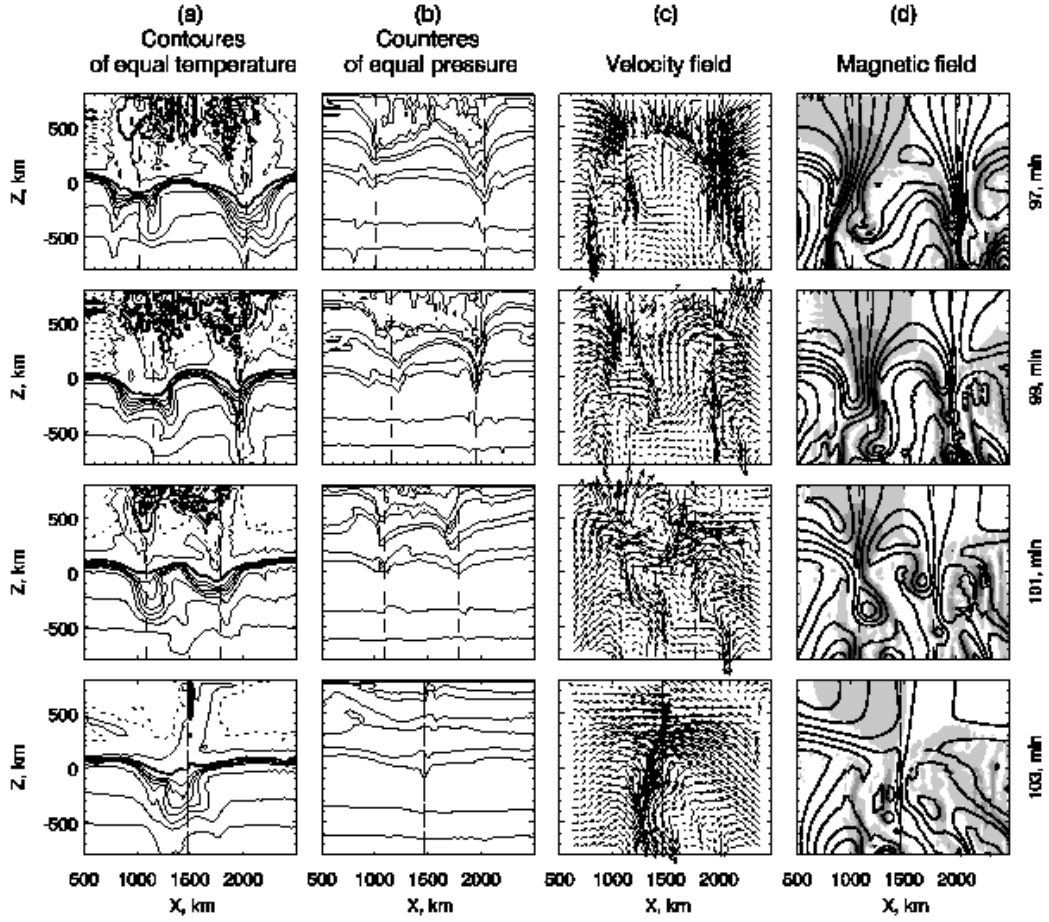


Figure 3: Spatial and temporal evolution of the dissipation of two magnetic tubes in the simulated region from 500–2500 km in the time interval 97–103 min. Format is the same as in Fig. 2.

are shifted toward the red part of the spectrum, and $V_V = 3.0$ km/s. The changes in the shape of the V profile (where the positive component is dominant) are the result of the increase in the longitudinal field with positive polarity.

Further, the formation of the downward jet continues at times 63–67 min. The stratification of the material increases. There is a deficit of the gas pressure, and the positive magnetic field is sharply amplified. The accelerated vertical flows carry cold material and the magnetic field downward. Hot walls are formed in the upper part of the channel due to compression. The strong magnetic flux reaches the bottom of the computational region. The amplitude of the V profile takes on its maximum values. The complete splitting of the profiles indicates that the field intensity in the tube reached kilogauss values ($B_{br} = 1078$ G). The redshift of the profiles is 3.3 km/s.

The subsequent times 71, 75, and 79 min demonstrate the evolution of a fully formed vertical magnetic tube with diameter 150 km at the $\log \tau_R = 0$ level, which is in a state of convective collapse. The kilogauss longitudinal magnetic field in the channel enters deeper layers. The I Stokes profiles are completely split during this interval ($B_{br} = 1246, 1195$, and 1231 G), the wing amplitudes have decreased, and the redshifts are large — $V_V = 4.9, 2.2$, and 3.4 km/s.

Thus, this fragment of magnetoconvection considered over an interval of 22 min (from 57 to 79 min with respect to the beginning of the simulation) shows that the surface

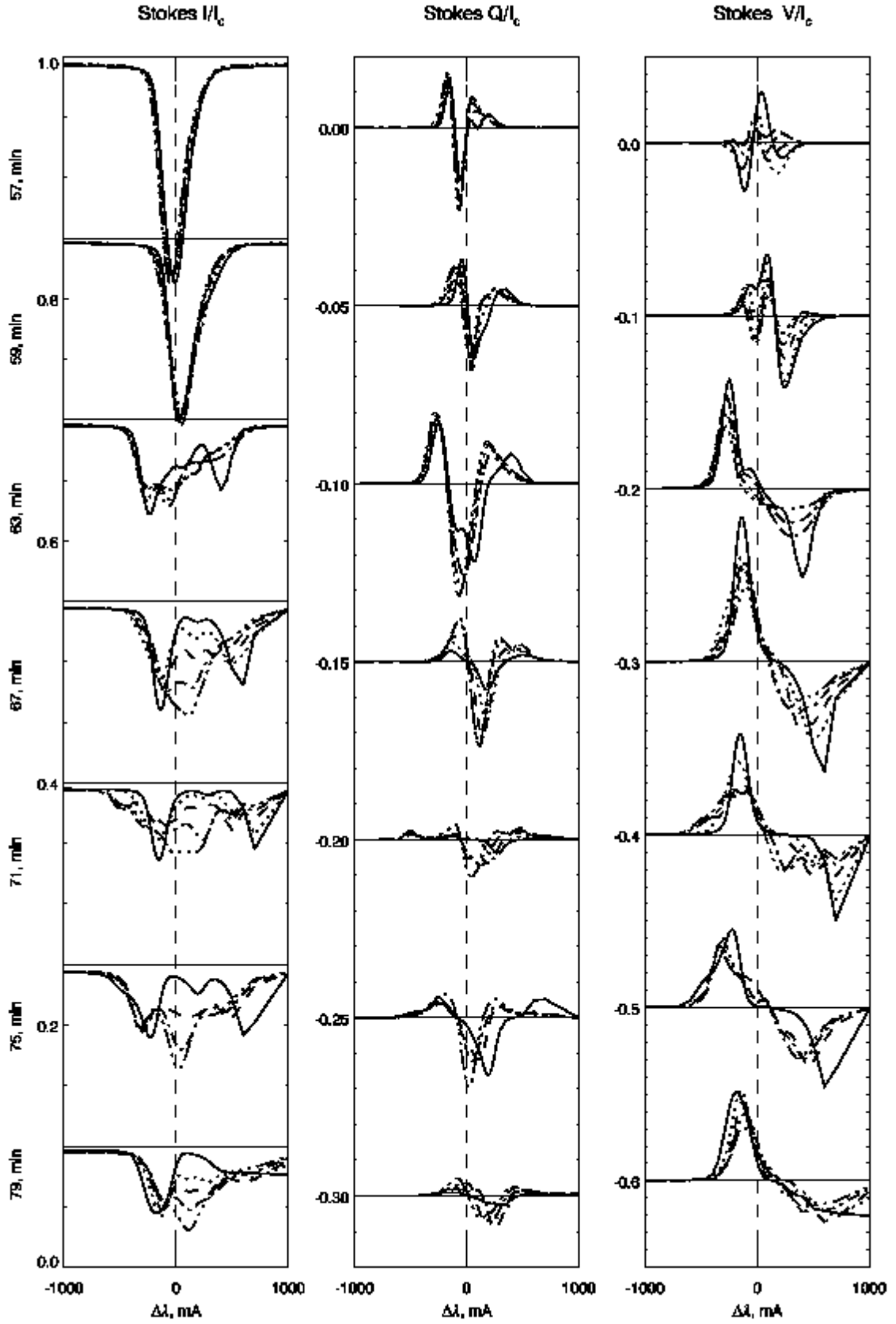


Figure 4: Stokes profiles of the Fe I 15648 Å line calculated at the center formation of the kilogauss tube (denoted by vertical dashed line in Fig. 2) for various spatial averaging scales: 35 km (solid curve), 105 km (dotted curve), 175 km (dashed curve), and 315 km (dot-dash curve).

mechanism for magnetic-tube formation reaches the stage of convective collapse during its development. The downward flow of material amplifies the magnetic flux in the channel to kilogauss values within 6–10 min. In the next 12 min, convective processes around the tube gather and push the magnetic field lines toward the channel, leading to further concentration of the field in the magnetic tube. These processes have an oscillatory character, due to the presence of both global oscillations of the entire computational region and oscillations of the tube by itself. In general, the characteristic spectral features of the evolution revealed by the simulations confirm the results obtained in [7].

4.2 Decay of magnetic tubes

Let us now consider a scenario for magnetic-field dissipation due to the forced merging of two tubes with opposite field directions, which is most typical of the simulations considered. The dynamics of these processes are shown in detail in Fig. 3, and the responses of the Stokes profiles calculated for each tube separately are presented in Fig. 5.

We can see two kilogauss vertical tubes with different field directions at time 97 min, separated by a distance of about 1000 km. The disintegration begins in the first, older, tube, which has a diameter of 350 km and positive polarity: the concentration of the magnetic flux decreases due to the tube’s separation and the appearance of upward motions in deep layers inside the tube. The magnetic field has already reached the bottom of the computational box; i.e., the kilogauss longitudinal magnetic field has entered deep layers. The profiles are completely split ($B_{br} = 1384$ G), have a regular shape, and are redshifted by 1.1 km/s.

The second tube, which has a smaller diameter (250 km) and negative polarity, is a well-developed intense magnetic tube with some signatures of superconvective instability: there are accelerated downward flows of material, a maximum concentration of longitudinal magnetic field along the entire tube down to the base of the model, a narrow region of downward motion with a gas-pressure deficit, a rarefied region at the top, and a strong Wilson depression. At this time, the distance between the peaks of the calculated V profile ($B_{br} = 1530$ G) and the redshift ($V_V = 5.0$ km/s) are maximum.

At subsequent times 99–101 min, the thermal flux separating the tubes disappears, and the two tubes with opposite magnetic-field directions begin to move toward each other, resulting in reconnection of the field lines. Characteristic motions similar to siphon flow can be seen between the tubes, whose features are described in detail in [16]. In the case under consideration, only magnetic-field lines between the tubes (rather than in the entire tube volume) participate in the siphon flows. This process decreases the magnetic field. In general, the dynamics of the motion are very complex. The flows of material in the tubes have considerably different velocity gradients and directions of motion. The upward flow increases in the positive tube, while the downward flow dominates inside the negative tube. Vortex motions appear between the tubes. All these processes result in disintegration of the tube structure and, accordingly, a rapid decrease in the magnetic-field concentration.

At time 101 min, the calculated V profile gives $V_V = -1.0$ km/s, $B_{br} = 700$ G for the first tube and $V_V = 0.7$ km/s, $B_{br} = 1166$ G for the second tube. At time 103 min, there is only a weak field with negative polarity in place of the two kilogauss tubes. A new powerful flow of material begins to move downward along the existing thermal channel with its pressure deficit. The profiles are appreciably shifted toward the red part of the spectrum, and the right wing is very broad ($V_V = 5.4$ km/s, $B_{br} = 656$ G).

Therefore, within a very short time interval of 6 min (from 97 to 103 min with respect to the beginning of the simulation), dissipation of the thermal flux (convective cell) separating

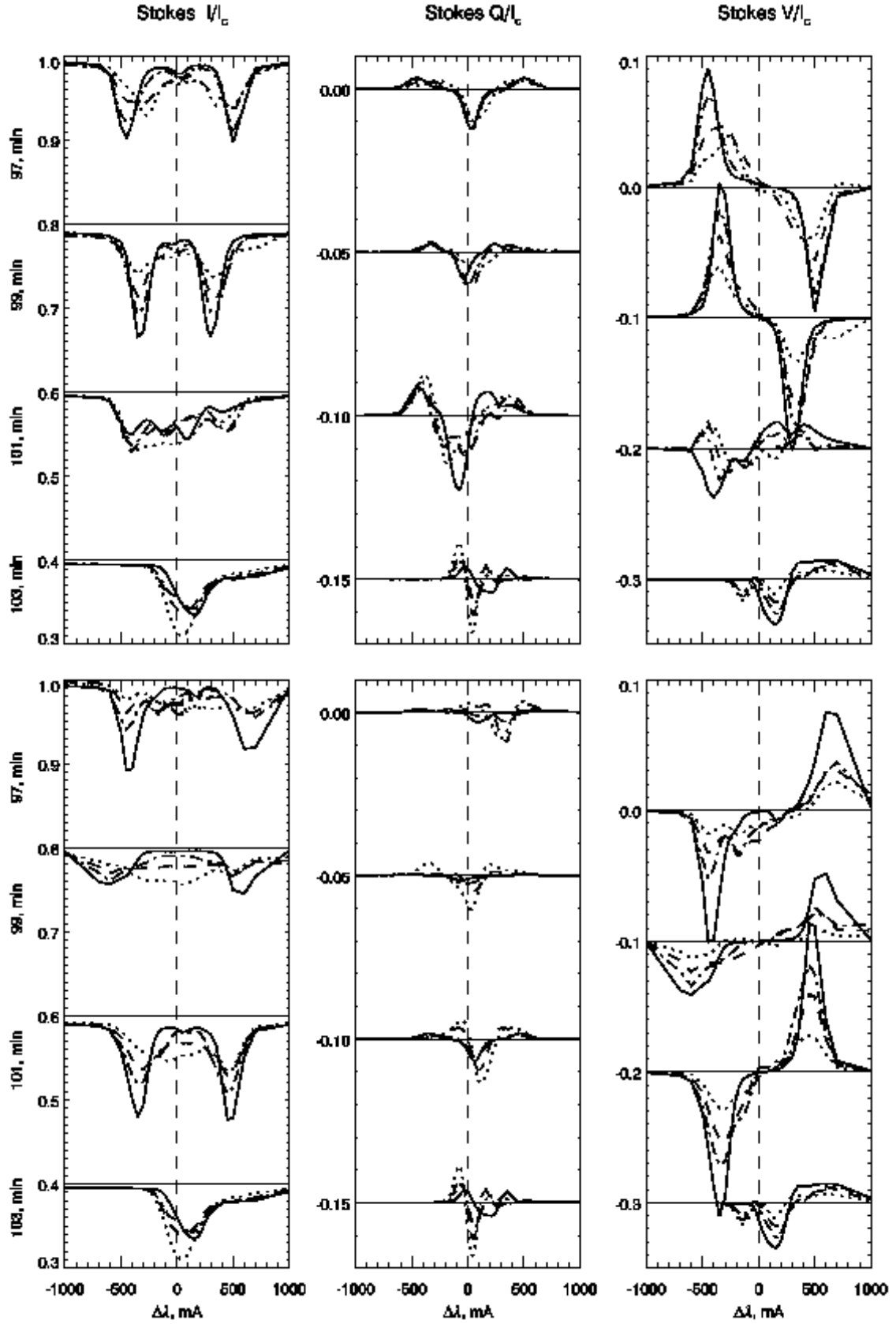


Figure 5: Stokes profiles of the Fe I 15648 Å line calculated at the center of the kilogauss tubes (denoted by vertical dashed line in Fig. 3) in regions where there is dissipation of these tubes. Top panels show Stokes I, Q, V profiles formed in a tube with positive magnetic-field polarity and bottom panels show the profiles formed in another tube with negative polarity. All designations are the same as in Fig. 4.

two tubes with opposite field directions led to merging of these compact magnetic elements and their disintegration.

4.3 Evolution of magnetic tubes and variations in the Stokes profiles

To trace the dynamics of temporal variations in the calculated Stokes profiles in the regions of formation and decay of the magnetic tubes, first and foremost, we studied the influence of spatial averaging on the results of Stokes diagnostics. This problem is considered in more detail in [14]. Figures 4 and 5 present the Stokes profiles calculated with various spatial averaging scales. A comparison of these profiles clearly shows that their shape substantially depends on the averaging region. The main reason for this is the complex structure of the simulated magnetic tube. The presence of appreciable horizontal and vertical gradients of the magnetic-tube parameters and of different directions for the magnetic field in the averaging region result in an anomalous shape for the Stokes profiles. The shapes are undistorted only for profiles calculated without horizontal averaging, i.e., for a single column in the tube center. Thus, only such profiles are able to reveal evolutionary spectral features. We used these profiles to calculate the parameters of the Stokes diagnostics, which are presented in Fig. 6 as functions of time.

As can be seen from the dependences in the left-hand side of Fig. 6, the following features are characteristic of the stage of magnetic-tube formation.

1. The distance between the σ_{\pm} , components of the V profiles in units of the magnetic-field intensity B_{br} reaches a maximum at times 71–79 min, when the tube experiences convective collapse.
2. The amplitude of the V profiles, a_V , increases, reaching its maximum just before the convective collapse, and then begins to decrease.
3. Redshifts of the profiles V_V predominate over the entire formation period and lifetime of the magnetic tube. They are plotted in velocity units in Fig. 6. The redshifts reach considerable values (up to 5 km/s) during the convective collapse.
4. The amplitude asymmetry of the V profiles δa is positive, varies in the range 0.02–0.3, and is correlated with redshift.
5. For the most part, the area asymmetry δA is negative and considerably less than δa .

The right-hand side of Fig. 6 presents the parameters of the Stokes diagnostics for the tube decay. The positive tube (solid line) begins to disappear at time 97 min, and the negative one (dotted line) at time 99 min. The resulting dependences can be summarized as follows.

1. The magnetic splitting of the profiles decreases.
2. The amplitude of the V profiles initially increases and then sharply decreases.
3. Blueshifts are dominant at the initial stage of disintegration of the tube. They also can reach considerable values (up to 5 km/s), but are observed for a substantially shorter time than are large redshifts.

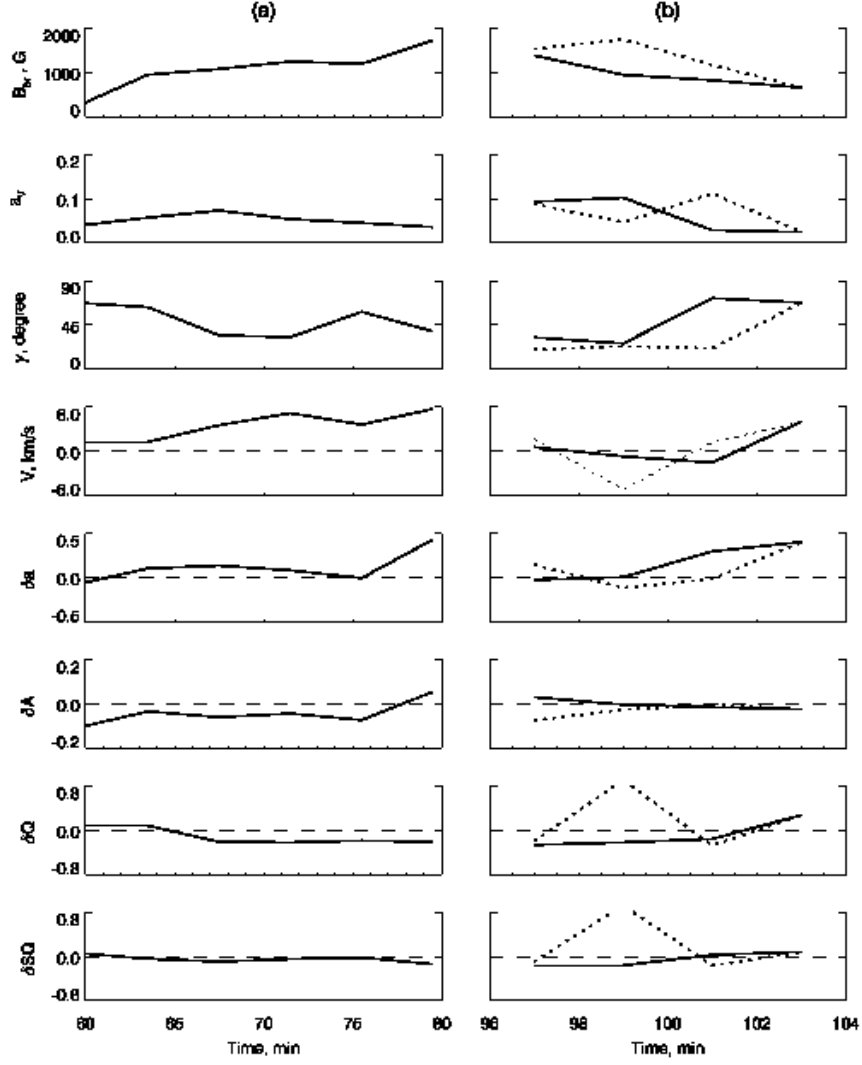


Figure 6: Variations in the parameters of Stokes diagnostics during (a) formation of the magnetic tube and (b) dissipation of two magnetic tubes. The solid and dotted lines correspond to the tubes with positive and negative magnetic field polarity, respectively. Here, B_{br} is the magnetic-field intensity, a_V is the amplitude of the V profile, V_V is the vertical velocity, and δa and δA are the amplitude and area asymmetries of the Stokes V.

4. The asymmetry of the V-profile amplitudes at the beginning of the disintegration is close to zero or is negative, but later becomes positive and increases.
5. The asymmetry of the V-profile areas slightly decreases during the disintegration of the tube.

The time dependences for the Stokes-profile parameters lead us to recommend measurement of shifts of the zero intersection of the Stokes V profiles as a practical diagnostic tool. Such shifts can be reliably determined from observations with high spatial and temporal resolution.

5 Conclusion

We have considered typical cases for the formation and decay of kilogauss magnetic tubes in association with corresponding temporal variations in the Stokes profiles of the Fe I 15648 Å infrared line. The most characteristic signature of convective collapse amplifying the magnetic field inside tubes to kilogauss values is extremely large redshifts of the Stokes V profiles and completely split I profiles. On the contrary, the tube dissipation process is characterized by blueshifts of the Stokes profiles, with typical features of weakening fields.

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